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**United States Patent**

(19)

Choi

[11] Patent Number: **5,675,394**[45] Date of Patent: **Oct. 7, 1997****[54] EQUALIZATION APPARATUS WITH  
EFFECTIVE COEFFICIENT UPDATING  
OPERATION****[75] Inventor:** Young-Bae Choi, Seoul, Rep. of Korea**[73] Assignee:** Daewoo Electronics Co., Ltd., Seoul,  
Rep. of Korea**[21] Appl. No.:** 572,401**[22] Filed:** Dec. 14, 1995**[30] Foreign Application Priority Data**

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[51] Int. Cl.<sup>6</sup> ..... H04N 5/21; H04N 5/44

[52] U.S. Cl. ..... 348/614; 348/775

[58] Field of Search ..... 348/725, 607,  
348/611, 614; 375/230, 232, 236; 364/724, 16,  
724.2; H04N 5/21, 5/44**[56] References Cited****U.S. PATENT DOCUMENTS**

4,791,390	12/1988	Harris et al.	.....	375/236
5,293,234	3/1994	Ko	.....	348/614
5,311,312	5/1994	Oh	.....	348/614
5,341,177	8/1994	Roy et al.	.....	348/614
5,479,449	12/1995	Patel et al.	.....	375/316
5,502,506	3/1996	Choi	.....	348/607
5,502,507	3/1996	Kim	.....	348/607

**OTHER PUBLICATIONS**

Y. S. Choi et al., "Adaptive Blind Equalization Coupled with Carrier Recovery for HDTV Modem", IEEE Transactions On Consumer Electronics, vol. 39, No. 3, Aug. 1993, pp. 386-391.

Hulyalkar et al., "Advanced Digital HDTV Transmission System for Terrestrial Video Simulcasting", IEEE Journal On Selected Area in Communications, vol. 11, No. 1, Jan. 1993, pp. 119-125.

Hulyalkar et al., "Advanced Digital HDTV Transmission System For Terrestrial Video Simulcasting", Jul. 1993, vol. No. 1, pp. 119-126.

*Primary Examiner*—John K. Peng*Assistant Examiner*—Jeffrey S. Murrell*Attorney, Agent, or Firm*—Anderson Kill & Olick P.C.**[57] ABSTRACT**

An equalization apparatus for use in a television system includes a equalizer filter having a plurality of equalizer coefficients and an updating circuit. In the updating circuit, the equalizer coefficients are adjusted by using two computational terms: a CMA term; and a Cauchy term in order to effectively make the equalizer to converge to the global minimum of the coarse MSE function all the time. Both terms decrease to zero as the equalizer coefficients approach to a minimum, but in different ways: the first CMA term decreases to zero monotonously; and the value of the second Cauchy term fluctuates up and down, depending on the selected value for the Cauchy distribution function and thus temporary increases, although contained, are allowed during the process. A combination of the two terms with a proper choice for the weight factors prevents the equalizer coefficients from converging to a local minimum of the coarse MSE function and makes them converge to the global minimum thereof all the time.

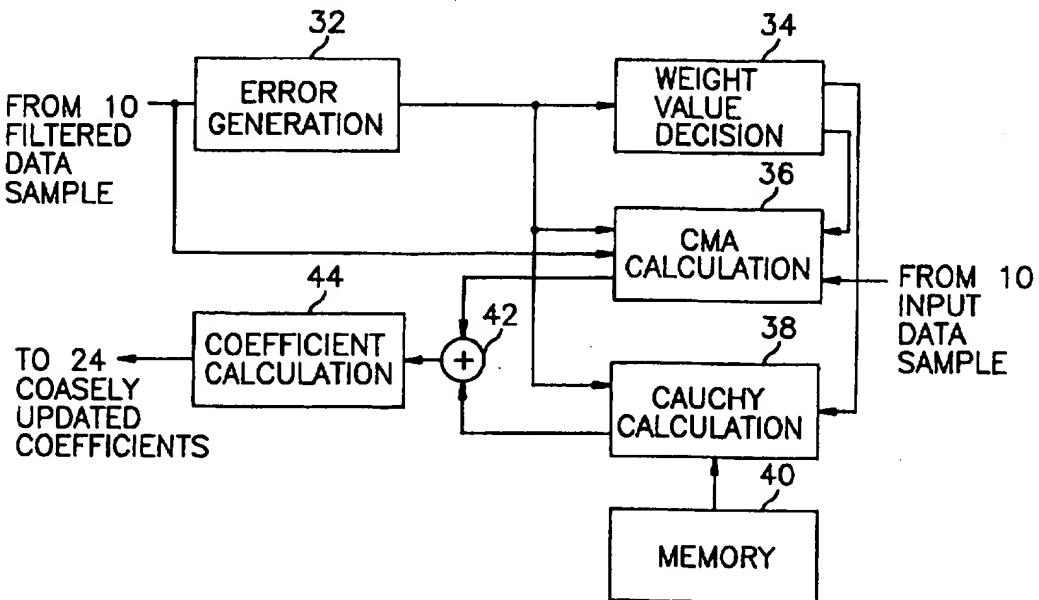
**4 Claims, 2 Drawing Sheets**

FIG. 1

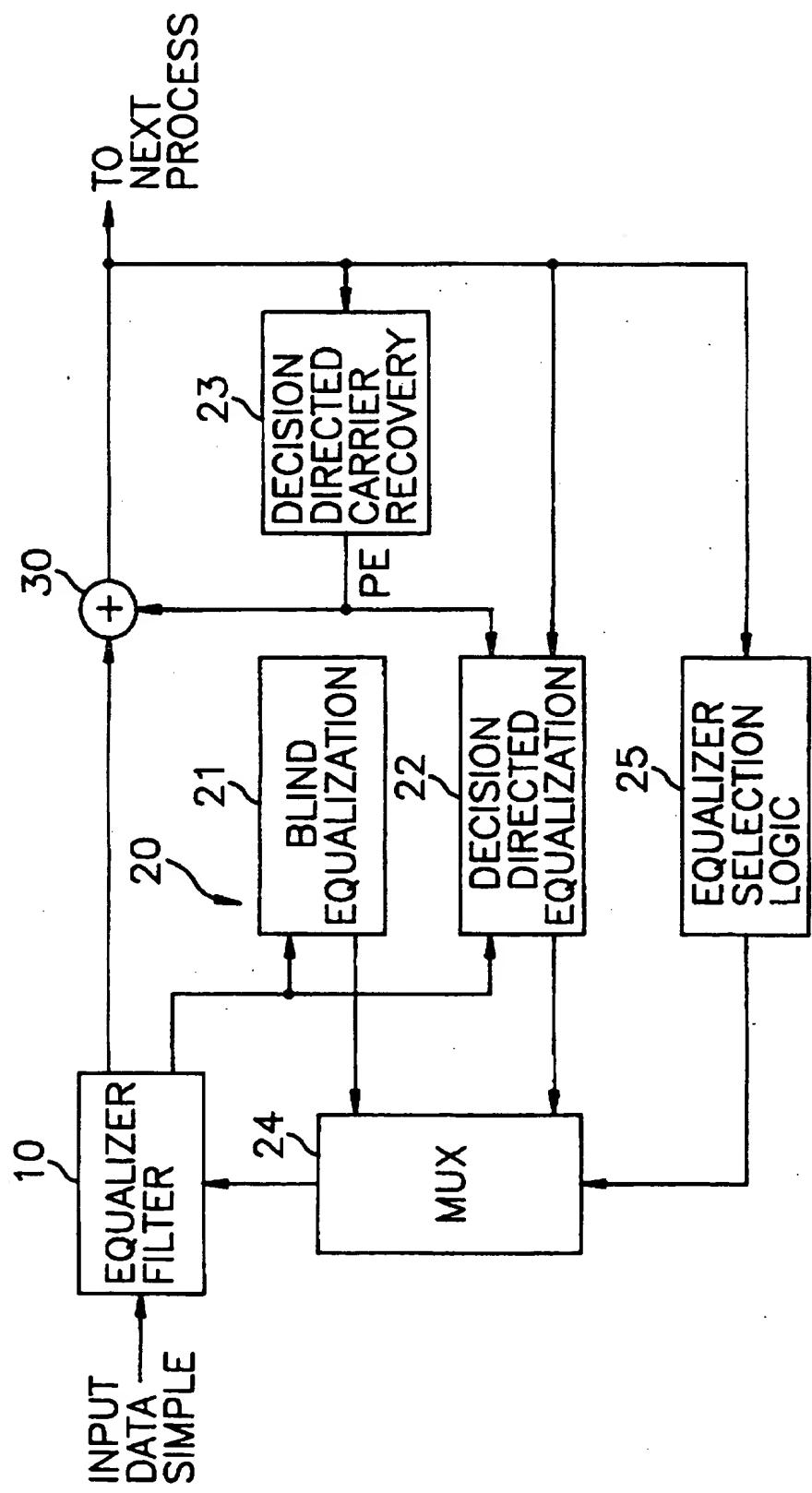
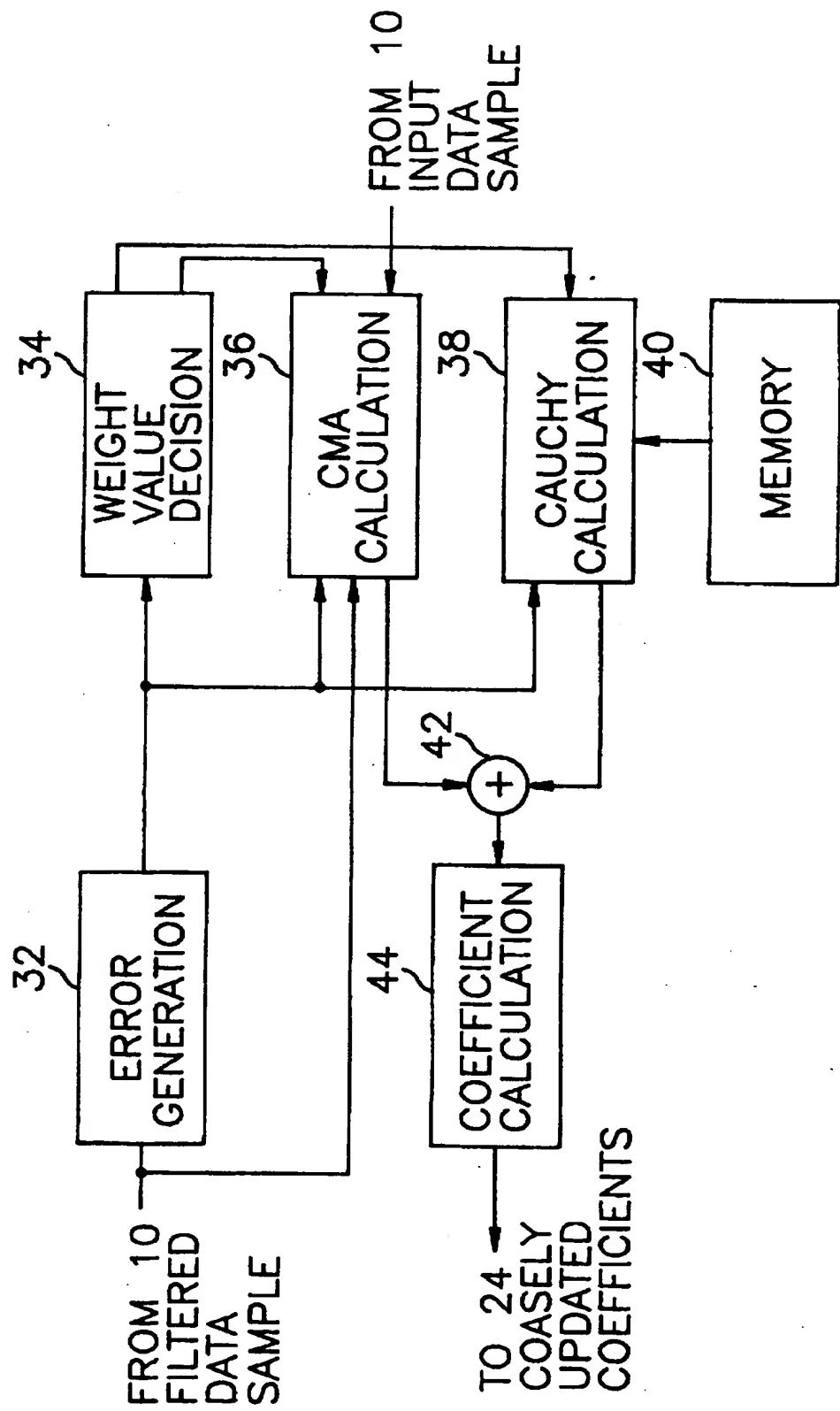


FIG. 2



## EQUALIZATION APPARATUS WITH EFFECTIVE COEFFICIENT UPDATING OPERATION

### FIELD OF THE INVENTION

The invention relates to an equalization apparatus for use in a high definition television (HDTV) signal receiving system; and, more particularly, to an improved equalization apparatus which is capable of providing an effective coefficient updating operation.

### DESCRIPTION OF THE PRIOR ART

In a HDTV system, television signals from a television signal transmission source are transmitted over a transmission channel to a HDTV signal receiving system. One inherent problem associated with the transmission of television signals over the transmission channel is that channel distortions and additive noises tend to disrupt, e.g., data symbols contained in the transmitted television signal, thereby adversely affecting the ability of the HDTV signal receiving system to distinguish the received symbol levels. To ameliorate this problem, a typical HDTV signal receiving system includes a channel adaptive equalizer.

Such a prior art channel adaptive equalizer employs a filtering device that removes from a received signal amplitude and phase distortions resulting from, e.g., a frequency dependent time-variant response of the transmission channel, to thereby provide an improved symbol decision capability.

One of such equalization apparatus for use in a HDTV signal receiving system is disclosed in an article by Samir N. Hulyalkar et al., "Advanced Digital HDTV Transmission System for Terrestrial Video Simulcasting", *IEEE Journal on Selected Areas in Communications*, 11, No. 1, pp 119-125 (January, 1993), which includes a finite impulse response (FIR) filter employing a plurality of equalizer coefficients called tap coefficients and a coefficient updating module to provide a self-adjustment without using a training sequence. The coefficient updating module is operated in two modes: a blind mode and a decision directed mode. In the blind mode, the equalizer coefficients are coarsely adjusted to their coarse initial values, corresponding to a coarse error function wherein the coarse error function is calculated by employing a known nonlinear function, i.e., the so-called cost function represented by a higher order equation. In the decision directed mode, the equalizer coefficients are finely updated to their optimum values by using a decision error function wherein the decision error function is calculated by using a known decision function. The initial values for the equalizer coefficients mentioned above are obtained in an iterative process by requiring that the differentiation of the cost function is reduced to zero, thereby allowing the cost function to converge to a minimum value. In this case, however, the cost function sometimes converges to a local minimum value instead of a global minimum. As a result, it is difficult to correctly adjust the equalizer coefficients to initial optimum values corresponding to the global minimum value of the error function.

### SUMMARY OF THE INVENTION

It is, therefore, a primary object of this invention to provide an improved television signal equalization apparatus which is capable of converging equalizer coefficients to their optimum values.

In accordance with the invention, there is provided an equalization apparatus for use in a television signal receiv-

ing system, which includes an equalizing filter having a set of equalizer coefficients for equalizing an input television signal distorted from an original signal in a transmission channel to produce a filtered output signal, wherein the input television signal includes a plurality of data samples and the filtered output signal has a corresponding plurality of filtered output data samples; and an updating circuit for generating, in response to a data sample and a filtered output data sample corresponding thereto, a set of updated equalizer coefficients as the set of equalizer coefficients for the equalizer filter, characterized in that said updating circuit comprises:

error generating means, in response to the filtered output data sample, for generating an error value denoting the difference between the filtered output data sample and a predetermined expected value and for generating a means square error value of the error value;

memory means for storing the set of updated equalizer coefficients as a set of previous equalizer coefficients and for storing a predetermined step size;

first calculation means for multiplying the data sample, the filtered output data sample, the predetermined step size and the error value to generate a first calculation value;

second calculation means for multiplying the error value with a random value arbitrarily selected from a known Cauchy distribution function to provide a second calculation value;

weighting means, based on the means square error value, for multiplying the first calculation value with a first weight factor and the second calculation value with a second weight factor to thereby generate a first and a second weighted calculation values; and

means for adding the first and the second weighted calculation values to the set of previous equalizer coefficients to produce a set of updated equalizer coefficients as an output of the updating circuit.

### BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects and features of the present invention will become apparent from the following description of preferred embodiments given in conjunction with the accompanying drawings, in which:

FIG. 1 shows a schematic block diagram of a television signal equalization apparatus employing a blind equalization block in accordance with the present invention; and

FIG. 2 depicts a detailed block diagram of the blind equalization block shown in FIG. 1.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, there is shown a television signal equalization apparatus employing a blind equalization block in accordance with the present invention. The television signal equalization apparatus includes an equalizer filter 10 having a multiplicity of equalizer coefficients, and a coefficient update module 20 for generating updated coefficients.

A television signal received from a transmission channel (not shown) is sampled at a known sampling circuit (not shown) into a plurality of input data samples which are sequentially coupled to the equalizer filter 10. The first equalizer filter 10 includes a finite impulse response (FIR) filter, wherein the input data samples are sequentially filtered and equalized by the multiplicity of equalizer coefficients contained therein in order to produce filtered data samples. The filtered data samples are then sequentially coupled to

the coefficient update module 20 and via a derotator 30 to a next processor, e.g., a source decoder(not shown).

That is, input data samples  $y(n)$ 's are sequentially and iteratively filtered by the equalizer filter 10 to correct the input data samples  $y(n)$ 's distorted in the transmission channel by using the equalizer coefficients and to produce filtered data samples as equalized data samples that approximate the original non-distorted data samples prior to their transmission.

As is known, the filtered data sample  $z(n)$  from the equalizer filter 10 may be represented as follows:

$$z(n) = \sum_{i=0}^{M_n-1} w_i(n) y \left( n - \frac{M_n}{2} + i \right) \quad (1)$$

wherein  $w_i(n)$  is a set of equalizer coefficients corresponding to  $M_n$  data samples adjacent to a target input data sample  $y(n)$  contained the equalizer filter where  $M_n$  is a positive integer representing the number of filter cells.

The equalizer coefficients  $w(n)$ 's are iteratively updated by the coefficient updating module 20 until satisfactory equalized samples are obtained. These coefficients and may be represented as follows:

$$w(n+1) = w(n) + \Delta y(n) e(n) \quad (2)$$

wherein  $\Delta$  is a small number, e.g.,  $2^{-10}$  or  $-12$  representing a scale factor and  $e(n)$  is an error function denoting a difference between the filtered data sample and a non-distorted data sample.

The iteration for updating the filter coefficients  $w(n)$ 's in the coefficient update module 20 continues until an optimum set of equalizer coefficients  $w(n)$ 's is reached and the filtered data samples  $z(n)$ 's, as the equalized data samples which approximate the original data samples, are obtained by the equalizer filter 10 using the optimum set of equalizer coefficients.

The coefficient update module 20, as described in the article by Samir N. Hulyalkar et al., is operated in two mode, i.e., a blind mode and a decision directed mode; and includes a blind equalization block 21, a decision directed equalization block 22 and a decision directed carrier recovery block 23. In the blind mode, the blind equalization block 21 receives the filtered data samples from the equalizer filter 10 and generates coarsely updated equalizer coefficients providing a coarse initial convergence which are coupled via a multiplexer 24 to the equalizer filter 10. In the equalizer filter 10, the coarsely updated equalizer coefficients supersede the previous equalizer coefficients contained therein. This process is repeated until a satisfactory initial convergence is achieved.

On the other hand, in the decision directed mode, the decision directed equalization block 22 receives the filtered data samples from the equalization filter 10 and a phase error PE from the decision-directed carrier recovery block 23; and generates finely updated coefficients by employing a least mean square(LMS) algorithm to achieve an optimum convergence of the equalizer coefficients. The decision-directed carrier recovery block 23 is also operated in the decision directed mode and generates the phase error PE which is coupled to the decision directed equalization block 22 and the derotator 30 in order to minimize the phase offset between the original data samples prior to transmission and the corresponding input data samples. The finely updated coefficients providing the optimum convergence are coupled via the multiplexer 24 to the equalizer filter 10 and supersede previous equalizer coefficients kept therein. This process is repeated until satisfactory equalized data samples are obtained.

The mode change operation is controlled by an equalizer selection logic circuit 25 that generates two mode selection signals: a blind mode selection signal and a decision directed mode selection signal. The equalizer selection logic circuit 25 receives the equalized data samples via the derotator 30 and calculates a mean square error(MSE) value thereof. The MSE value is compared with a first predetermined error value which can be experimentally determined on a basis of so-termed eye pattern which represents the amount of intersymbol interference and noise in a digital communication system and is measured by using a conventional oscilloscope. When the MSE value is greater than the first predetermined error value, the equalizer selection logic circuit 25 generates a blind mode selection signal that actuates the multiplexer 24 in order to couple the coarsely updated equalizer coefficients outputted from the blind equalization block 21 as the updated equalizer coefficients to the equalizer filter 10.

On the other hand, when the MSE value is identical to or smaller than the first predetermined error value, the equalizer selection logic circuit 25 produces a decision directed mode selection signal that couples the finely updated equalizer coefficients outputted from the decision directed equalization block 22 via the multiplexer 24 to the equalizer filter 10 as the updated equalizer coefficients.

The coarsely updated equalizer coefficients described above may be iteratively adjusted by employing a coarse means square error function instead of error function  $e(n)$ , wherein the coarse means square error(MSE) function can be represented by a cost function denoting a known nonlinear function with respect to the equalizer coefficients. Specifically, as described in the article by Samir N. Hulyalkar et al., the blind equalization block 21 utilizes a known constant modulus algorithm (CMA) having a cost function represented by a fourth degree equation for the purpose of reducing the hardware complexity. In this case, the cost function  $D^{(2)}$  denoting the coarse MSE function is known to be represented as follows:

$$D^{(2)} = E[z(n)^2 - R_2]^2 \quad (3)$$

wherein  $z(n)$  is the filtered data sample previously defined in Eq. (1);  $R_2$  is a positive real constant representing a mean radius of a constellation of original data samples (e.g.,  $R_2=26.186$  for 32-quadrature amplitude modulation (QAM) based television system); and  $E$  is an expectation function.

Therefore, minimization of the coarse MSE function can be achieved by minimizing the cost function  $D^{(2)}$  which can be expressed in terms of the equalizer coefficients  $w(n)$  defined in Eq. (1). Accordingly, minimization of the cost function  $D^{(2)}$  with respect to the equalizer coefficients can be performed recursively according to a known steepest decent method. Therefore, a coarsely updated equalizer coefficient  $w(n)$  can be expressed in terms of the cost function  $D^{(2)}$  as follows:

$$w(n+1) = w(n) - \delta \left[ \frac{dD^{(2)}}{dw(n)} \right] \quad (4)$$

wherein  $\delta$  is a step-size parameter.

Following a well known standard step in the art, by differentiating the cost function  $D^{(2)}$  in Eq. (4), a coarsely updated equalizer coefficient  $w(n)$  can be obtained and represented as follows:

$$w(n+1) = w(n) + \mu y(n) z(n) [z(n)^2 - R_2] \quad (5)$$

where  $\mu$  is a small number, e.g.,  $2^{-10}$  or  $-12$ , representing a step-size parameter.

As may be seen from Eqs. (4) and (5), the error function can be represented by a cost function of a fourth degree equation with respect to the equalizer coefficients, wherein the fourth degree equation may have a global minimum and a local minimum. As the differentiation of the cost function is gradually reduced to zero by using the steepest decent method, the equalizer coefficients converge to a minimum of the coarse MSE function. In this case, however, the equalizer coefficients sometimes converge to a local minimum of the coarse MSE function instead of its global minimum.

Therefore, in accordance with the present invention, in order to make the equalizer coefficients to converge to the global minimum of the coarse MSE function all the time, Eq. (5) is modified as follows:

$$w(n+1) = w(n) + \eta [ \mu y(n) z(n) (|z(n)|^2 - R_2) + (1-\eta) (|z(n)|^2 - R_2) C(k) ] \quad (6)$$

where  $\eta$  is a positive real constant denoting a weight factor and  $C(k)$  is a Cauchy distribution function well known in the art.

As may be seen from Eq. (6), in the blind equalization block 21 in accordance with the present invention, the equalizer coefficients  $w(n)$ 's are adjusted by using two computational terms: a CMA term of  $\mu y(n) z(n) (|z(n)|^2 - R_2)$ ; and a Cauchy term of  $(|z(n)|^2 - R_2) C(k)$ , in order to effectively make the equalizer converge to the global minimum of the coarse MSE function all the time. Both terms decrease to zero as the equalizer coefficients approach to a minimum, but in different ways. As is well-known, the first CMA term decreases to zero monotonously. On the other hand, the value of the second Cauchy term fluctuates up and down, depending on the selected value for the Cauchy distribution function  $C(k)$  and thus temporary increases, albeit contained, are allowed during the process. A combination of the two terms with a proper choice for the weight factor  $\eta$  prevents the equalizer coefficients from converging to the local minimum of the coarse MSE function and leads them to converge to the global minimum thereof all the time.

Referring to FIG. 2, there is a detailed diagram of the blind equalization block for implementing Eq. (6). The blind equalization block 21 includes an error generation block 32, a weight value decision block 34, a CMA calculation block 36, a Cauchy calculation block 38, a memory 40, an adder 42 and a coefficient calculation block 44.

The filtered data samples are sequentially coupled to the error generation block 32 which generate an coarse error value denoting the difference between a filtered data sample and the mean radius of the constellation, and a coarse MSE value. The coarse error value is relayed to the weight value decision block 34 which compares the coarse MSE value obtained by the coarse error value with a second predetermined error value to generate first and second weight factors, wherein the second weight factor is determined as (1—first weight factor). The second predetermined error value is determined as a value slightly greater than the first predetermined error value. The first weight factor is relayed to the CMA calculation block 36 and the second weight factor is inputted to the CMA calculation block 38. As may be seen from Eq. (6), when the coarse MSE value is greater than the second predetermined error value, the first weight factor is determined as a small number and, therefore, the second weight factor is determined as a number greater than the first weight factor.

The coarse error value is simultaneously inputted to the CMA calculation block 36 and the Cauchy calculation block 38. The CMA calculation block 36 receives the input data sample, the filtered data sample, the coarse error value and

the first weight factor to produce a CMA calculation value by multiplying them. The Cauchy calculation block 38 receives the coarse error value, the second weight factor and a random Cauchy value from the memory 40 to generate a Cauchy calculation value, wherein the random Cauchy values are selected from the catchy distribution function and randomly prestored in the memory 40.

The CMA and the catchy calculation values are combined in an adder 42 to produce a combined value. The combined value is then provided to the coefficient calculation block 44 which adds the combined value to the previous equalizer coefficients stored therein to produce the coarsely updated equalizer coefficients wherein the coefficient calculation block 44 includes a memory which has a multiplicity of memory locations storing the coarsely updated equalizer coefficients as the previous equalizer coefficients. The previous equalizer coefficients of the equalizer filter are then updated at the coarsely updated equalizer coefficients in the blind mode.

As described above, the set of equalizer coefficients is iteratively and effectively updated by using the input data samples and the coarse error value until an optimum initial set of equalizer coefficients is obtained.

While the present invention has been described with respect to certain preferred embodiments only, other modifications and variations may be made without departing from the spirit and scope of the present invention as set forth in the following claims.

What is claimed is:

1. An equalization apparatus for use in a television signal receiving system, which includes an equalizing filter having a set of equalizer coefficients for equalizing an input television signal distorted from an original signal to produce a filtered output signal, wherein the input television signal includes a plurality of data samples and the filtered output signal has a corresponding plurality of filtered output data samples; and an updating circuit for generating, in response to a data sample and a filtered output data sample corresponding thereto, a set of updated equalizer coefficients as the set of equalizer coefficients for the equalizer filter, characterized in that said updating circuit comprises:

error generating means, in response to the filtered output data sample, for generating an error value denoting the difference between the filtered output data sample and a predetermined expected value and for generating a mean square error value of the error value;

weight factor generation means for generating a first weight factor and a second weight factor based on the mean square value, wherein the second weight factor is determined as (1—the first weight factor);

memory means for storing the set of updated equalizer coefficients as a set of previous equalizer coefficients; first calculation means for multiplying the data sample, the filtered output data sample, a predetermined step size, the first weight factor and the error value to generate a first calculation value;

second calculation means for multiplying the second weight factor, the error value and a random value arbitrarily selected from a Cauchy distribution function to provide a second calculation value; and means for adding the first and the second calculation values to the set of previous equalizer coefficients to produce a set of updated equalizer coefficients as the set of equalizer coefficients for the equalizer filter.

2. The equalization apparatus as recited in claim 1, wherein the second calculation mean includes a memory for

storing a multiplicity of random values constituting the Cauchy distribution function.

3. The equalization apparatus as recited in claim 2, wherein the error value  $e(n)$  is represented as:

$$e(n) = (z(n))^2 - R_2$$

wherein  $z(n)$  is the filtered output data sample and  $R_2$  is a positive real constant representing a mean radius of a constellation of original data samples.

4. The equalization apparatus as recited in claim 3, wherein the updated equalizer coefficient  $w(n+1)$  is represented as:

$$w(n+1) = w(n) + \eta [(\mu y(n) z(n) (z(n))^2 - R_2) + (1 - \eta) ((z(n))^2 - R_2) C(k)]$$

5 wherein  $\eta$  is a positive real constant denoting the first weight factor;  $(1 - \eta)$  is the second weight factor;  $\mu$  is a small number representing the predetermined step size;  $y(n)$  is the data sample;  $w(n)$  is a previous equalizer coefficient and  $C(k)$  is the random value selected from the Cauchy distribution function.

\* \* \* \* \*

United States Patent [19]  
Foschini

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[45] Date of Patent: Dec. 23, 1986

[54] CROSS-POLARIZATION  
CANCELER/EQUALIZER

[75] Inventor: Gerard J. Foschini, Sayreville, N.J.

[73] Assignee: AT&T Bell Laboratories, Murray Hill, N.J.

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[52] U.S. Cl. ..... 375/15; 375/102; 375/103; 455/295

[58] Field of Search ..... 370/6, 20; 455/60, 273, 455/276, 278, 283, 295, 303, 306; 375/14, 15, 39, 100, 103, 102; 364/724; 333/18, 20, 28 R; 179/170.2, 170.6; 343/361, 362, 383

[56] References Cited

U.S. PATENT DOCUMENTS

3,391,339 7/1968 Lynch ..... 370/20  
4,053,837 10/1977 Ryan et al. ..... 375/15  
4,074,086 2/1978 Falconer et al. ..... 179/170.2  
4,112,370 9/1978 Monsen ..... 375/14  
4,283,795 8/1981 Steinberger ..... 455/283  
4,306,307 12/1981 Levy et al. ..... 375/39  
4,321,705 3/1982 Namiki ..... 375/14  
4,349,889 9/1982 van den Elzen et al. ..... 364/724  
4,369,519 1/1983 Yuuki et al. ..... 455/60  
4,412,341 10/1983 Gersho et al. ..... 375/102  
4,479,258 10/1984 Namiki ..... 455/295  
4,521,878 6/1985 Toyonaga ..... 375/39  
4,577,330 3/1986 Kavehrad ..... 375/15

OTHER PUBLICATIONS

Ehrenbard et al., Globecom '82, Miami, Fla., vol. 2, pp. D8.4.1-D8.4.5.

Van Gerwin et al., IEEE Jnl. Sel. Areas Comm., vol. SAC-2, No. 2, Mar. 1984, pp. 314-323.

Sato, IEEE Trans. Comm., vol. COM-23, No. 6, Jun. 1975, pp. 679-682.

Mueller, BSTJ, vol. 58, No. 2, Feb. 1979, pp. 491-500.

Godard, IEEE Trans. Comm., vol. COM-28, No. 11, Nov. 1980, pp. 1867-1875.

Gersho et al., BSTJ, vol. 60, No. 11, Nov. 1981, pp. 1997-2021.

Mueller et al., BSTJ, vol. 60, No. 11, Nov. 1981, pp. 2023-2038.

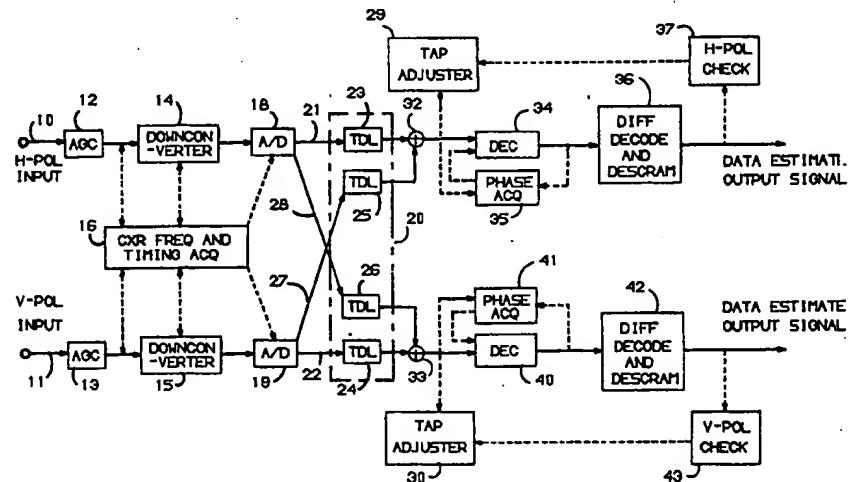
Holte et al., IEEE Trans. Comm., vol. COM-29, No. 11, Nov. 1981, pp. 1573-1581.

Primary Examiner—Benedict V. Safourek  
Attorney, Agent, or Firm—Erwin W. Pfeifle

[57] ABSTRACT

The present invention relates to a cross-polarization equalizer/canceler which simultaneously performs cross-polarization equalization/cancellation in a tapped delay line (TDL) matrix. More particularly, the present equalizer/canceler receives the first and second orthogonally polarized digital signals on separate paths which are each split into a straight through and cross-over paths that include a TDL matrix comprising a separate TDL, with a predetermined number of complex taps, in each of the paths. The individual complex taps are appropriately adjusted in response to control signals from a tap adjusting means which derives the appropriate control signals from current tap signals and computed gradients derived from a predetermined algorithm. Accurate data decisions, however, are not needed. The resultant TDL output signals in the merging straight-through and cross-over paths at the output of the TDL matrix are combined to converge each of the polarized signals for propagation along the straight-through paths.

4 Claims, 3 Drawing Figures



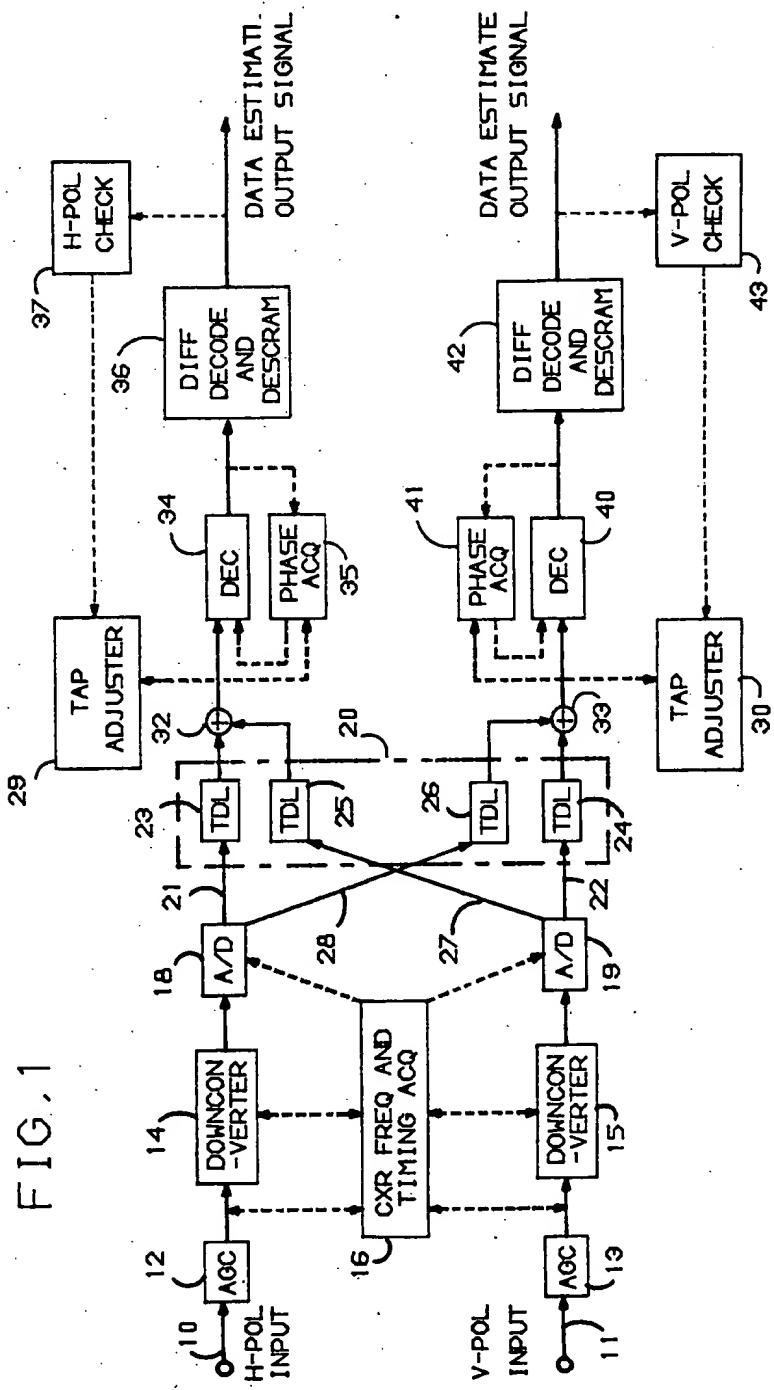
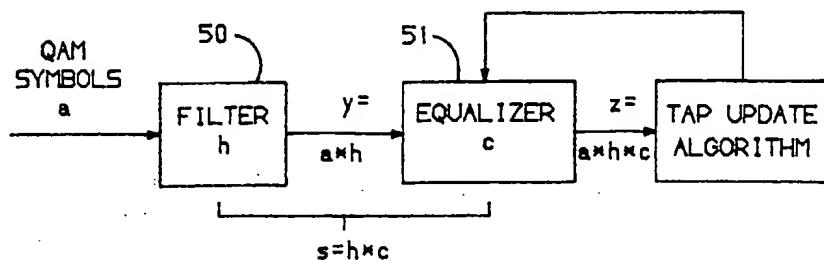
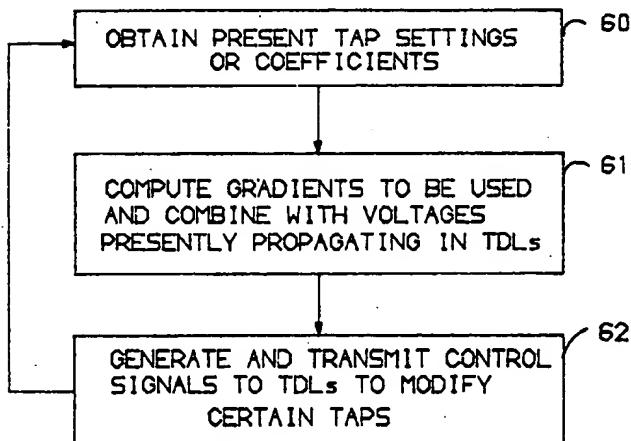


FIG. 2



a, h, c, y, z, AND s ARE ALL DOUBLY INFINITE COMPLEX SEQUENCES

FIG. 3



CROSS-POLARIZATION  
CANCELER/EQUALIZER

## TECHNICAL FIELD

The present invention relates to a cross-polarization canceler/equalizer which concurrently performs equalization and cross-polarization cancellation.

## DESCRIPTION OF THE PRIOR ART

Transmission systems that use electromagnetic waves can take full advantage of the transverse nature of these waves by utilizing two distinct states of polarization to increase channel capacity without using additional bandwidth. Dual-polarization transmission has been used extensively in satellite communications and is receiving considerable attention for terrestrial radio. A propagation medium other than empty space will, in general, depolarize the electromagnetic waves, with the result of introducing cross-polarization coupling between the two distinct polarization channels.

Cross-polarization cancelers have been devised to reduce or substantially cancel cross-polarization components received in each of the polarization channels. One such arrangement is disclosed in U.S. Pat. No. 4,283,795 issued to M. L. Steinberger on Aug. 11, 1981. There, a first desired polarized signal and a second interfering orthogonally polarized signal, are concurrently received and transmitted along separate paths. The two signals are recombined after the phase and amplitude of the second interfering signal have been appropriately adjusted to maximally cancel the cross-polarization components in the desired signal. A feedback path is provided to obtain a sample of any remaining interfering signal in the recombined signal, generate a signal representative of the power envelope of such sample, and then generate appropriate control signals to provide improved adjustment of the amplitude and phase of the received orthogonally polarized interfering signal sample.

The use of equalization has also been discussed in the article "Self-Recovering Equalization And Carrier Tracking In A Two-Dimensional Data Communication System" by D. N. Godard in *IEEE Transactions On Communications*, Vol. COM-28, No. 11, November 1980 at pages 1867-1875. The article, however, does not provide a proof that such equalization will converge for all nonzero initial tap settings.

The problem in the prior art is to provide a cross-polarization cancellation technique which will provide concurrent cross-polarization cancellation and equalization to remove all elements of cross-polarization interference in received orthogonally polarized signals without requiring data decisions and without insertion of equalizer training signals.

## SUMMARY OF THE INVENTION

The foregoing problem in the prior art has been solved in accordance with the present invention which relates to a cross-polarization canceler/equalizer which concurrently performs equalization and cross-polarization cancellation.

It is an aspect of the present invention to provide a cross-polarization canceler/equalizer which includes a tapped delay line matrix in the main and cross-over paths of the canceler/equalizer, and a separate feedback path including a tap adjuster means for each polarized signal, with each tap adjuster means connecting to the

appropriate tapped delay lines of the matrix for adjusting the appropriate associated complex taps to effect concurrent equalization and cross-polarization cancellation.

5 It is a further aspect of the present invention to provide a cross-polarization canceler/equalizer which concurrently performs equalization and cross-polarization cancellation without the need for accurate data decisions at the output of the canceler/equalizer. Additionally, the canceler/equalizer does not require a special modification of the transmitted signal to provide the cancellation/equalization function.

10 Other and further aspects of the present invention will become apparent during the course of the following description and by reference to the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings:

FIG. 1 is a block diagram of a cross-polarization canceler/equalizer in accordance with the present invention.

FIG. 2 is a block diagram of an equivalent baseband model for single polarization transmission; and

FIG. 3 is a flow diagram for each of the tap adjusting means of FIG. 1 for generating the appropriate tap matrix settings.

## DETAILED DESCRIPTION

For purposes of illustration, it will be assumed that a dually polarized Quadrature Amplitude Modulation (QAM) signal pair is being received after propagating through a medium subjected to slowly, random varying, frequency selective fades and cross-polarization coupling. On certain occasions the loss of signal can be so complete that an optimum receiver could not detect the data. Subsequently, a strong signal returns but carrier and timing may have wandered and the medium may have significantly changed its dispersive character. It is desirable to detect the data symbols as soon as the signal strength returns. It is the uncertainty about the various features of the received signal, apart from the inherent uncertainty associated with the information symbols and additive noise, that slows the recapture process. Carrier frequency and phase, and timing frequency and phase are all to some degree uncertain. Moreover, the 2x2 matrix transfer characteristic of a dispersive medium is also uncertain where the diagonal elements of the matrix describe the co-polarization transfer characteristics, and the off-diagonal terms express the couplings between polarizations. Such medium must be equalized to enable accurate data detection as well as providing cross-polarization cancellation. The present invention provides a method of simultaneous equalization and cross-polarization cancellation that does not require the availability of data estimates.

FIG. 1 is a block diagram of a cross-polarization canceler/equalizer in accordance with the present invention which receives the horizontally and vertically polarized signals, and the associated cross-polarized components, at separate inputs terminals 10 and 11, respectively. The horizontally and vertically polarized signals from input terminals 10 and 11 are passed through a first and second Automatic Gain Control (AGC) circuit 12 and 13, respectively, which function to limit the input analog polarized signal within a predetermined threshold. The output signals from AGCs 12

and 13 provide an input to Downconversion means 14 and 15, respectively, and to a carrier frequency and timing acquisition means 16. Carrier frequency and timing acquisition means 16 functions to recover the carrier frequency and timing of the exemplary dually polarized QAM received input signals. Downconversion means 14 and 15 each function to downconvert the input analog signal of the associated polarized signal in accordance with signals from carrier frequency means 16. It will be assumed hereinafter that conversion is to baseband. However, IF or even RF versions of the present invention are possible.

The dually polarized analog output signal samples from a demodulator and sampling means in Downconversion means 14 and 15 are converted to corresponding digital signals in Analog-to-Digital (A/D) converters 18 and 19, respectively, using timing control signals from carrier frequency and timing acquisition means 16. The digital output signals from A/D converters 18 and 19 are then passed through a tapped delay line (TDL) matrix 20 comprising TDLs 23 and 24 disposed in the straight-through horizontally and vertically polarized received signal paths 21 and 22, respectively, and TDLs 25 and 26 disposed in respective cross-over paths 27 and 28 to provide the simultaneous cross-polarization cancellation and equalization function in accordance with the present invention. More particularly, the Horizontal and Vertical digital signal samples are transmitted into tapped delay line matrix 20 which is responsive to control signals from tap adjusting means 29 and 30 associated with the horizontally polarized signal TDLs 23 and 25 and vertically polarized signal TDLs 24 and 26, respectively. Each of TDLs 23-26 are usually identical with the other TDLs and comprise a tapped delay line including a plurality of complex taps which configuration is well known in the art. The number of taps to be used in each of TDLs 23-26 is arbitrary and depends on the dispersiveness of the medium the signals propagate through in the path between the transmitter and receiver, and the accuracy desired in the equalized and cross-polarized canceled decoded data estimates. Therefore, the number of taps desired can be determined experimentally, with the number of taps being directly related to the dispersiveness of the medium and the accuracy desired.

The TDL sections 24,25 and 23,26 of matrix 20 function to appropriately adjust the amplitude and phase of the signals of the vertically and horizontally polarized signals, respectively, from respective A/D converters 19 and 18. The outputs from TDL sections 23 and 25 of TDL matrix 20, associated with the desired horizontally polarized signal and the interfering cross-polarized components from the received vertically polarized signals on paths 21 and 27, respectively, are added in adder means 32 to provide simultaneous equalization and cross-polarization cancellation for the desired horizontally polarized signal. Similarly, the outputs from TDL sections 24 and 26 of TDL matrix 20, associated with the desired vertically polarized signal and the interfering cross-polarized components from the received horizontally polarized signals on paths 22 and 28, respectively, are added in adder means 33 to provide simultaneous equalization and cross-polarization cancellation for the desired vertically polarized signal. It is to be understood that TDLs 23-26 of matrix 20 each function to provide some simultaneous equalization and cross-polarization component adjustment in the signal propagating therethrough rather than just TDLs 25 and

26 in the cross-over paths providing cross-polarization cancellation while other means provide the necessary equalization.

The output signal from adder means 32 is transmitted to a decision means 34 which makes decisions on the digital symbols based on input signals from each of adder means 32, a phase acquisition circuit 35 and tap adjusting means 29. The output from decision means 34 is differentially decoded and descrambled, if originally scrambled, in differential decoding and descrambling means 36 to obtain the data estimate output signals associated with the received horizontally polarized signal. What should be understood is that the present equalizer/canceler is capable of converging to provide a substantially pure signal, but that in converging it may be converging on another signal being received such as, for example, in path 21 the arrangement may converge onto the received vertically polarized signal rather than the desired received horizontally polarized signal. It is known to somehow differently scramble or separately identify each of the originally transmitted signals using, for example, a different code. The resultant descrambled signal is received in a polarization check circuit 37 to make sure the descrambled signal is the proper one by checking, for example, that the resultant data signal is understandable and was scrambled with the proper code, or includes the proper identifier. Horizontal polarization check circuit 37, therefore, functions to make sure that the canceler/equalizer is locked onto the right polarization.

Similarly, the output signal from adder means 33 is transmitted to a decision means 40 which makes decisions by estimating digital symbols based on input signals from each of adder means 33, a phase acquisition circuit 41, and tap adjusting means 30. The output signal from decision means 40 is differentially decoded and descrambled, if originally scrambled, in a differential decoding and descrambling means 42 to obtain the data estimate output signals associated with the received vertically polarized signal. The output signals from differential decoding and descrambling means 42 are also received by a vertical polarization check circuit 43 which functions to make sure that the canceler/equalizer is locked onto the vertically polarized received signal at the output of differential decoding and descrambling means 42. If either one of check circuits 37 or 43 provides a check indicating that a wrong signal has been locked onto, the canceler/equalizer is made to reinitialize. For example, if one of the output signals is a wrong signal, only the TDLs of TDL matrix 20 associated with the equalization/cancellation for that signal need be reinitialized. If both the output signals are locked onto the oppositely polarized signals, then the option of just switching the two output signals can be exercised rather than reinitialization. The output signals from check circuits 37 and 43, therefore, include control signals indicating whether or not the proper polarized signal has been locked onto, and such indications are provided as inputs to tap adjusting means 29 and 30, respectively. Tap adjusting means 29 and 30 each function in accordance with a predetermined algorithm to provide the appropriate control signals to TDLs 23-26 to converge the signals at the output of adder means 32 and 33. The following discussion is presented to provide an understanding of this predetermined algorithm for effecting the simultaneous equalization and cross-polarization cancellation function.

It is to be understood that Godard in his paper "Self-Recovering Equalization and Carrier Tracking In Two-Dimensional Data Communication Systems" in *IEEE Transactions on Communications*, Vol. COM-18, No. 11, November 1980 at pages 1867-1875 discusses a technique or algorithm to provide only equalization, but could not prove that an arrangement using the algorithm would converge at all times. Additionally, Godard did not disclose or suggest the possibility of simultaneous equalization and cross-polarization cancellation. In accordance with the present invention, an algorithm, which is used in tap adjusting means 29 and 30, has been developed which will converge a  $2 \times 2$  matrix equalizer so that the overall system response decouples the two polarizations. The taps in the TDLs 23-26 15 evolve in accordance with a gradient of a vector potential. Upon convergence, the phase needs to be recovered by phase acquisition means 35 which can include, for example, separate phase lock loops.

As was stated hereinbefore, there is a possibility that, 20 despite the perfect locking onto one polarization and the consequent perfect removal of the other polarization, the polarizations could be transposed. This ambiguity is easily resolved, as was stated hereinbefore, by using known "tagging" or "identifying" techniques 25 with each polarization by, for example, the scrambling process. Once checking means 37 and 43 determine that the proper signal is received and send such indication to tap adjusting means 29 and 30, respectively, tap adjusting means 29 and 30 use the input signals from respective decision means 34 and 40, the respective phase acquisition means 35 and 41 and especially the present voltages at the taps of the TDLs 23-26 to determine the new tap values for convergence.

To explain the function of each of tap adjusting 35 means 29 and 30, some notations are required which can be defined using an equivalent baseband QAM model shown in FIG. 2. The complex input data sequence in FIG. 2 is denoted as  $a$ . The elements of  $a = (\dots a_0, a_1, \dots)$  represent independent and identically distributed 40 choices from a QAM constellation, each point of which is equally likely. This is normalized so that  $E|a_n|^2 = 1$ .

The complete sequence  $h$  in filtering means 50 represents samples of the impulse response of the transmitter and medium combination. The sequence  $c$  in equalizer 45 means 51 represents the complex equalizer taps. Using the  $*$  symbol for convolution, the sampled impulse response of the channel and equalizer in combination is denoted  $s = h * c$ , the received data is denoted  $y = a * h$ , and the sequence after the equalizer is  $z = a * h * c$ . This notation is consistent with the notation of Godard. Also,  $h$  is assumed to have a continuous Fourier transform devoid of spectral nulls. Consequently,  $h$  has a convolution inverse  $h^{-1}$  satisfying  $h * h^{-1} = 010$ . By 55 an infinite sequence of zeroes is meant, left directed if preceding a number and right directed if following a number. If 0 is written without abutting a number, it means the sequence of zeroes extending from  $-\infty$  to  $+\infty$ . A more refined model of the terrestrial digital radio environment would include additive white Gaussian noise at the input to the receiver. However, the major interest here is in prompt reestablishment of adequate equalization after a cataclysmic event during which the data detection capability was completely lost (so  $P_e \approx \frac{1}{2}$ ). The situation is that the medium, despite the 65 presence of additive noise, has the potential of providing adequate performance if only the equalizer could be properly aligned. In such situations, the SNR is gener-

ally so large that an optimal minimum means square (MMSE) equalizer, including noise effects, is only slightly better than an inverse equalizer, which neglects noise. Once the equalization can provide for a  $P_e$  in the neighborhood of 0.01 to 0.1, conventional linear (MMSE) equalization is an assumed option. Moving from the model of FIG. 2 to the arrangement of FIG. 1, a two dimensional setting is needed to account for horizontally and vertically polarized signals. Here  $c$  and  $h$  are  $2 \times 2$  matrices. The vectors  $(z_H, z_V)$  and  $(a, b)$  are related as follows:

$$\begin{bmatrix} z_H \\ z_V \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \cdot \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} \quad (1)$$

The individual elements of  $z_H$ ,  $z_V$ ,  $a$  and  $b$  are denoted by subscripts. We use  $s$  to denote the matrix:

$$c^*h = \begin{bmatrix} c_{11}h_{11} + c_{12}h_{21} & c_{11}h_{12} + c_{12}h_{22} \\ c_{21}h_{11} + c_{22}h_{21} & c_{21}h_{12} + c_{22}h_{22} \end{bmatrix} \quad (2)$$

The matrix  $h$  is assumed to be nonsingular so that  $h^{-1}$  exists:

$$h^{-1} * h = \begin{bmatrix} 0,1 & 0 & 0 \\ 0 & 0,1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (3)$$

The components of the vector  $(a, b)$  represent the QAM data sequence driving the horizontal and vertical polarizations. Of course, the elements of  $a$  and  $b$  are all independent and a vector criterion is employed to obtain the approximate gradients to be applied to each complex tap of TDLs 23-26 in accordance with the equation:

$$\begin{bmatrix} \min E (|z_{Hn}|^2 - E|a_n|^4)^2 \\ (c_{11}c_{12}) \\ \min E (|z_{Vn}|^2 - E|b_n|^4)^2 \\ (c_{21}c_{22}) \end{bmatrix} \quad (4)$$

It should be noted that optimization of these two components proceeds independently of each other in that the first component involves  $c_{11}$  and  $c_{12}$  while the second involves  $c_{21}$  and  $c_{22}$ . Therefore, tap adjusting means 29 and 30 operate in accordance with the top and bottom expressions, respectively, of Equation (4).

Each of tap adjusting means 29 and 30 can comprise, for example, a microcomputer and an associated memory for storing the sequence of instructions for performing the steps shown in FIG. 3 including the calculations using Equation (4) above. More particularly, as shown in FIG. 3, each of tap adjusting means 29 and 30 operate to (a) take the present tap coefficients or settings, indicated in box 60, which may be stored in a scratchpad portion of the memory of the microcomputer; (b) compute the gradients in accordance with Equation (4) and add those gradients to the voltage values determined as presently propagating in TDLs 23-26, as indicating in box 61, to determine the new complex tap settings for convergence; and (c) use the determined new tap settings to generate and transmit appropriate control signals to TDLs 23-26 for modifying these complex tap

settings to a desired new value as indicated in box 62. It is to be understood that each complex tap setting is preferably modified one predetermined step size at a time to provide convergence, but could use more than one step size if desired.

The feature that the algorithm appears to have no preference as to which tap should be a reference tap implies that, with finitely many taps, the tap weight distribution could crowd to one end of the equalizer. To avoid a lopsided tap weight distribution in TDLs 23-26, the center of gravity of the tap weights could periodically be computed, e.g., every few hundred symbols, and then shift the weights to situate the balance point as close as possible to a central tap of each TDL. A computationally simpler alternative to the center of gravity method described hereinabove is to periodically compare the weights of the first and last tap of each TDL and then shift tap weights by one in the direction of the least weight.

In the foregoing discussion, it is to be understood that elements 12-16 and 18-19 of FIG. 1 are merely provided for purposes of illustration as a technique for providing dually polarized signals as separate inputs to the TDL matrix 20 for effecting the simultaneous equalization and cross-polarization cancellation function in accordance with the present invention. Similarly, other and further modifications could be made to the arrangement of FIG. 1 and still stay within the spirit and scope of the present inventive concept.

What is claimed is:

1. A cross-polarization equalizer/canceler for concurrently equalizing and canceling cross-polarization components in a first and a second orthogonally polarized digital signal, the equalizer/canceler comprising:
  - a first and second input terminals for receiving the first and second orthogonally polarized signal, 35 respectively;
  - a first and a second straight-through path (21,22) coupled to the first and second input terminal, respectively;
  - a tapped delay line matrix (20) comprising a separate tapped delay line (TDL) in each of the first and second straight-through paths and each of the first and second cross-over paths, each TDL including a plurality of complex taps which are individually responsive to control signals for appropriately changing a current tap setting and a resultant output signal of each TDL;
  - a first adder means (32) for adding the output signals from the TDLs in the first straight-through path and the second cross-over path;
  - 50 a second adder means (33) for adding the output signals from the TDLs in the second straight-through path and the first cross-over path; and
  - tap adjusting means (29, 30) coupled to the output of the first and second adder means and to the complex taps of the TDLs in the TDL matrix for generating appropriate control signals to the complex taps of the TDL matrix for appropriately changing the tap settings to effect concurrent equalization and cross-polarization component convergence in each of the first and second orthogonally polarized signals at the output of the first and second adder means, respectively, the tap adjusting means generating the appropriate control signals to each of the complex taps as derived from the addition of an associated current complex tap signal and an updated gradient representative of a vector of the component of the associated TDL signal in accordance with the relationship

$$\min_E (|z_{Hn}|^2 - E|a_n|^4)^2 \\ (c_{11}c_{12})$$

$$\min_E (|z_m|^2 - E|b_n|^4)^2 \\ (c_{21}c_{22})$$

where E represents an average of the associated term;  $a_n$  and  $b_n$  are the  $n^{th}$  complex data symbol of the first and second orthogonally polarized signals, respectively;  $z_{Hn}$  and  $z_m$  are the complex samples at time  $nT$  of the first and second orthogonally polarized signals, respectively, at the output of the respective first and second adder means; and  $c_{ij}$  identify a TDL within the TDL matrix where i and j designate the input to output path, respectively, of the TDL and 1 and 2 indicate the respective first and second orthogonally polarized signals.

2. A cross-polarization equalizer/canceler according to claim 1 wherein the first and second orthogonally polarized signals include separate Quadrature Amplitude Modulated (QAM) encoded signals, and

the tap adjusting means derives the appropriate gradients to be added to the current complex tap signals in accordance with the relationship

$$\left[ \begin{array}{l} \min_E (|z_{Hn}|^2 - E|a_n|^4)^2 \\ (c_{11}c_{12}) \\ \min_E (|z_m|^2 - E|b_n|^4)^2 \\ (c_{21}c_{22}) \end{array} \right]$$

where E represents an average of the associated term;  $a_n$  and  $b_n$  are the  $n^{th}$  complex data symbol of the first and second orthogonally polarized signals, respectively;  $z_{Hn}$  and  $z_m$  are the complex samples at time  $nT$  of the first and second orthogonally polarized signals, respectively, at the output of the respective first and second adder means; and  $c_{ij}$  identify a TDL within the TDL matrix where i and j designate the input to output path, respectively, of the TDL and 1 and 2 indicate the respective first and second orthogonally polarized signals.

3. A cross-polarization equalizer/canceler according to claim 1 wherein each of the first and second orthogonally polarized input signals includes a different encoded identification means, the equalizer/canceler further comprising:

means (37, 43) responsive to the output signals from the first and second adder means for separately checking the encoded identification of each the output signals to determine whether the output signals from the first and second adder means are the converged first and second orthogonally polarized signals, respectively, and for generating a first and second output signal to the tap adjusting means indicative of a respective match or non-match of the encoded identification for each of the converged output signals; and

the tap adjusting means includes means responsive to a second output signal from the identification checking means for causing a reinitialization of the TDL matrix to a predetermined setting.

4. A cross-polarization equalizer/canceler according to claim 1 wherein the tap adjusting means comprises: means for periodically comparing the weight distribution at the complex taps of each TDL of the TDL matrix and for changing the overall tap weight distribution of the complex taps in the TDLs to provide a balance point substantially at the central taps of the TDLs.

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